

Heavy Squarks and Light Sleptons in Gauge Mediation

From the viewpoint of 125 GeV Higgs Boson and Muon $g - 2$

Masahiro Ibe^(a,b), Shigeki Matsumoto^(b),
Tsutomu T. Yanagida^(b), and Norimi Yokozaki^(b)

^(a)*ICRR, University of Tokyo, Kashiwa, 277-8583, Japan*

^(b)*Kavli IPMU, University of Tokyo, Kashiwa, 277-8583, Japan*

Abstract

In the framework of gauge mediation models, we investigate scenarios with heavy squarks and light sleptons, motivated by the recent discovery of the Higgs boson and the deviation of the muon anomalous magnetic moment ($g - 2$) from the SM prediction. We show that only models with a messenger multiplet in the adjoint representation of $SU(5)$ GUT gauge group are the unique possibility that sleptons are light enough to explain the muon $g - 2$ in the minimal setup. We also show that, if there is an additional source of the Higgs soft masses, the muon $g - 2$ can be explained with messenger multiples in the fundamental representation of $SU(5)$ with the help of the light higgsino. Some phenomenological aspects of these models are also discussed.

1 Introduction

The latest results from the ATLAS and CMS collaborations show a 5σ signal for a Higgs-like boson mass at around 125 GeV [1, 2]. The results have significant impacts on the model building of the supersymmetric (SUSY) standard model (SSM). For example, a lightest Higgs boson mass around 125 GeV requires large stop masses of $\mathcal{O}(10 - 100)$ TeV [3, 4] (see, e.g., [5] for recent discussion) or large stop A -term [4] in the minimal SSM (MSSM). In other cases, the 125 GeV Higgs boson mass requires some extensions of the MSSM, such as models with massive extra matter fields coupling to the Higgs doublets [6], models with extra gauge interactions [7], or models with a singlet fields coupling to the Higgs doublet, e.g., the next-to-minimal SSM (NMSSM) (see [8, 9] for recent reviews).

On another front, the seeming discrepancy of the muon anomalous magnetic moment (a_μ) between theoretical predictions and experimental results has been a strong motivation to expect that superparticles are discovered in the near future at the LHC experiments. In the SSM, the discrepancy can be resolved when the superparticles, especially sleptons as well as the higgsino, wino and bino are in the mass range of $\mathcal{O}(100)$ GeV. Such expectations are, however, getting disappointed (especially in the MSSM) due to the unexpectedly heavy Higgs boson mass which tends to require the superparticle masses in the TeV range or above.

In response to this situation, it is imperative to investigate whether or not the 125 GeV Higgs boson mass and the discrepancy of the anomalous magnetic moment can be explained simultaneously in the models of the SSM. It has been shown that both can be achieved in the MSSM with gauge mediation where a large A -term is generated due to the mixing between Higgs doublets and messenger fields [10]. It has also been shown that both can also be achieved simultaneously in the extensions of the MSSM with extra matter fields [11],¹ or extra gauge interactions [13].

In this paper, we discuss an alternative possibility to explain the Higgs boson mass of 125 GeV and a_μ in models with heavy squarks and light sleptons based on the models with gauge mediation. In this scenario, the Higgs boson mass is explained by heavy stop masses at $\mathcal{O}(10)$ TeV, while the discrepancy of a_μ is explained by light sleptons. As we will see later, this apparently effortless possibility is highly constrained. As a result, we find that the model with messenger fields in the adjoint

¹The higgsino mass of $\mathcal{O}(1)$ TeV as well as the SUSY masses of the extra matters can be related to the PQ-symmetry breaking scale [12].

24 representation of the $SU(5)$ gauge group of the grand unified theory (GUT) is the unique possibility to explain both Higgs boson mass and a_μ by the heavy squark and the light slepton spectrum. We also show that the models with messengers in fundamental $\mathbf{5} + \bar{\mathbf{5}}$ representations can also explain the Higgs boson mass and a_μ , once we admit extra contributions to the Higgs soft squared masses.

This paper is organized as follows. In section 2, we discuss generic conditions to explain the Higgs boson mass and a_μ on models with heavy squarks and light sleptons. In section 3, we discuss the model with messenger fields in the adjoint representation. In section 4, we discuss models with additional Higgs soft squared masses. The final section is devoted to summary of our discussions.

2 Muon $g - 2$ vs. heavy squarks

The muon anomalous magnetic moment ($a_\mu = g - 2$) has been measured very precisely, and it is an important probe of new physics beyond the standard model (SM). The current experimental value of the anomalous magnetic moment is [14]:

$$a_\mu^{\text{exp}} = 11659208.9(6.3) \times 10^{-10}. \quad (1)$$

The most recent calculation of the SM prediction, on the other hand, is [15];

$$a_\mu^{\text{SM}} = 11659182.8(4.9) \times 10^{-10}, \quad (2)$$

which includes the updated data from " $e^+e^- \rightarrow \text{hadrons}$ " processes and the latest evaluation of the hadronic light-by-light scattering contributions. As a result, the experimental result and the SM prediction deviate with each other by about 3.3σ ,

$$\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10}. \quad (3)$$

In the MSSM, δa_μ can be resolved by supersymmetric contributions when the sleptons (smuons) as well as the higgsino and/or the wino and the bino are in the range of $\mathcal{O}(100)$ GeV. In our scenario, the stop masses are expected to be $\mathcal{O}(10)$ TeV to explain the 125 GeV Higgs boson mass.² To achieve such heavy squark masses, we first assume that messenger fields with color charges generate

$$m_{\text{squark}} \sim \frac{g_3^2}{16\pi^2} \frac{F_c}{M_c} = \mathcal{O}(10) \text{ TeV}, \quad (4)$$

²It is worth noting that A -terms are suppressed in models with gauge mediation. As discussed in references [16, 10], sizable A -terms can be achieved by mixing messenger fields and Higgs doublets even in models with gauge mediation, though we do not peruse in this paper.

where g_3 denotes the $SU(3)_C$ gauge coupling constant, while M_c and F_c are the mass and mass splitting of the colored messenger, respectively. The slepton masses are, on the other hand, expected to be of $\mathcal{O}(100)$ GeV for explaining the observed anomalous magnetic moment,

$$m_{\text{slepton}} \sim \frac{g_{1,2}^2}{16\pi^2} \frac{F_w}{M_w} = \mathcal{O}(100) \text{ GeV}, \quad (5)$$

where g_1 and g_2 denote the gauge couplings of $U(1)_Y$ and $SU(2)_L$ (the SM gauge group), while M_w and F_w are a mass and a mass splitting of the non-colored messenger, respectively. In the following discussions, we assume that the mass scales of the colored and non-colored messengers are close with each other, i.e. $M_c \simeq M_w \simeq M$, for simplicity. The mass splittings are, on the other hand, different from each other, and assumed to be hierarchical, i.e., $F_w \ll F_c$. Such different mass splittings are, for example, realized when couplings between the messenger fields and a supersymmetry breaking field depend on the fields whose vacuum expectation values break the GUT spontaneously. Notice that the different mass splitting $F_w \ll F_c$ we choose in the following discussion does not disturb the unification of the SM gauge coupling constants.

The above required separation between the squark and slepton masses as in Eqs. (4) and (5) is, however, not easily realized. For example, when the messenger is "a pair of fundamental and anti-fundamental representations", the colored messenger has non-vanishing $U(1)_Y$ charge, and hence, the right-handed sleptons obtain at least

$$m_{\text{slepton}} \sim \frac{3}{5\sqrt{2}} \frac{g_1^2}{g_3^2} \times m_{\text{squark}}. \quad (6)$$

The right-handed sleptons cannot be light as $\mathcal{O}(100)$ GeV for $m_{\text{squark}} = \mathcal{O}(10)$ TeV. Another complication comes from the size of the μ -term. Due to the stop masses of $\mathcal{O}(10)$ TeV, the Higgs soft squared masses ($m_{H_{u,d}}^2$) receive large radiative corrections,

$$\Delta m_{H_u}^2 \simeq \frac{6y_t^2}{16\pi^2} m_{\text{stop}}^2 \log \frac{m_{\text{stop}}^2}{M^2} = -[(3-4) \text{ TeV}]^2. \quad (7)$$

Here, y_t denotes the coupling constant of the top Yukawa interaction. In order to realize the Z -boson mass (m_Z), the μ -term is therefore required to satisfy

$$\mu^2 \simeq \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \frac{m_Z^2}{2} \simeq -\Delta m_{H_u}^2 = [(3-4) \text{ TeV}]^2, \quad (8)$$

where the Higgs mixing parameter $\tan \beta$ is assumed to be large enough, $\tan \beta = \mathcal{O}(10)$, to resolve the discrepancy of a_μ (see following discussions). We have also

used $m_{H_u}^2 \simeq \Delta m_{H_u}^2$, which is justified since the gauge mediated contributions to the Higgs soft squared are the same as those of the sleptons, and hence, much smaller than $\Delta m_{H_u}^2$.

When the higgsino is heavy, a dominant contribution to the anomalous magnetic moment comes from the one-loop diagram in which the bino, left-, and right-handed sleptons are circulating, which is evaluated to be

$$\delta a_\mu \simeq \frac{3}{5} \frac{g_1^2}{8\pi^2} \frac{m_\mu^2 \mu \tan \beta}{M_1^3} F_b, \quad (9)$$

where m_μ is the muon mass, M_1 the bino mass, and $F_b = \mathcal{O}(1)$ for $M_1 \simeq m_{\tilde{\mu}_R} \simeq m_{\tilde{\mu}_L}$ [17]. In order to resolve the discrepancy of a_μ , the bino, left-, and right-handed sleptons are therefore required to be light as less than about 200-500 GeV, depending on the size of the left-right mixing, $\mu \tan \beta$. Most of colored messengers, however, have non-vanishing $U(1)_Y$ charges as mentioned above, which prevents the sleptons and bino from being light enough. One exception is the messenger in color octet representation which is embedded in the adjoint **24** representation of the $SU(5)$ GUT gauge group. In this case, we can freely separate the squark and slepton masses, and hence, the desired spectrum can be obtained. As we will see in the next section, the discrepancy of a_μ can be actually reduced in models with the adjoint messenger, while it is difficult in models with messengers in other representations.

A possible way to avoid the above conclusion is to introduce additional contributions to the Higgs soft square masses other than the gauge mediated contributions. With such extra contributions, the radiative contributions to the Higgs soft square masses from the heavy stops in Eq. (7) can be fine-tuned to allow much smaller μ -term. In such cases, we have additional supersymmetric contributions to a_μ from the one-loop diagrams in which the light higgsinos are circulating. As we will show in section 4, the discrepancy of a_μ can be resolved with not very light sleptons; the light higgsino and wino enhance the SUSY contributions to the muon $g - 2$. In this way, models with messengers in other than the adjoint representations can also explain both the 125 GeV Higgs boson mass and the discrepancy of a_μ .

3 Messenger in adjoint representation

As we have discussed in previous section, the messenger in adjoint **24** representation gives the unique possibility to have light sleptons in separation with squark masses. The adjoint **24** messenger fields consist of Σ_8 , Σ_3 , X and \bar{X} , which are, respectively,

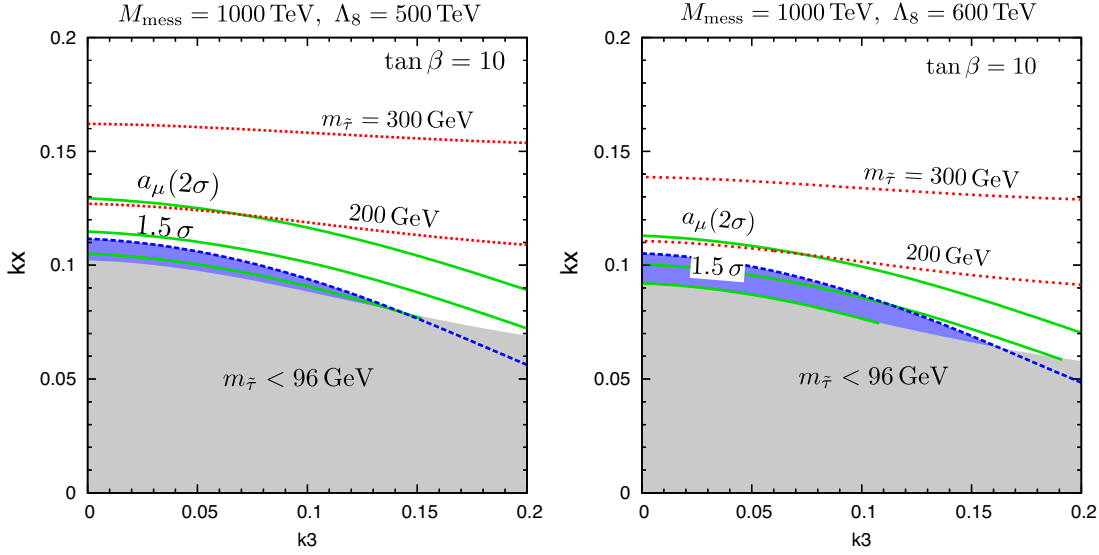


Figure 1: Contours of a_μ consistent with the experimental result at 2, 1.5, and 1σ C.L. (from top to bottom) on the k_3 - k_X plane for $\Lambda_8 = 500$ (left) and 600 TeV (right). The region below the dashed blue line is excluded because the electroweak symmetry minimum is not stable enough.

transformed as $(\mathbf{8}, \mathbf{1}, 0)$, $(\mathbf{1}, \mathbf{3}, 0)$, $(\mathbf{3}, \mathbf{2}, -5/6)$ and $(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ under the Standard model gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$. The superpotential is given by

$$W = (M_8 + k_8 F \theta^2) \text{Tr} \Sigma_8^2 + (M_3 + k_3 F \theta^2) \text{Tr} \Sigma_3^2 + (M_X + k_X F \theta^2) X \bar{X}. \quad (10)$$

We parameterize the SUSY breaking masses of the messengers by k_8 , k_3 and k_X . Since only relative size is important, we take $k_8 = 1$ in the following analysis. Formulas for the soft mass parameters are given in Appendix A.

In figure 1, several contours of a_μ are shown on the k_3 - k_X plane for the adjoint messengers with $\tan \beta = 10$. For simplicity, we take a common SUSY mass for the messengers, i.e., $M_8 = M_3 = M_X = M_{\text{mess}} = 10^6$ GeV. The mass spectrum and renormalization group evolution are evaluated using **SuSpect** [18] with appropriate modifications, while δa_μ (the SUSY contribution to a_μ) is calculated by **FeynHiggs** [19]. In the left (right) panel, $\Lambda_8 = F/M_8$ is taken to be $\Lambda_8 = 500$ (600) TeV, corresponding to the stop mass of $m_{\tilde{t}} \equiv (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2} \simeq 8$ (10) TeV. In the region below the dashed blue line is excluded due to the unstable electroweak symmetry breaking minimum [20, 21]. This is because the large left-right mixing of the stau generates a deep charge breaking minimum, making the electroweak symmetry breaking minimum meta-stable. We have evaluated the stability bound using the

| | | | |
|--------------------------------------|-----------------------|--------------------------------------|-----------------------|
| M_{mess} | 1000 TeV | M_{mess} | 1000 TeV |
| Λ_8 | 500 TeV | Λ_8 | 600 TeV |
| k_3 | 0.15 | k_3 | 0.16 |
| k_X | 0.08 | k_X | 0.07 |
| M_{bino} | 286 GeV | M_{bino} | 301 GeV |
| M_{wino} | 691 GeV | M_{wino} | 812 GeV |
| μ | 3.7 TeV | μ | 4.3 TeV |
| m_{gluino} | 9.9 TeV | m_{gluino} | 11.9 TeV |
| $m_{\tilde{t}}$ | 8.2 TeV | $m_{\tilde{t}}$ | 9.7 TeV |
| $m_{\tilde{q}}$ | 8.8 TeV | $m_{\tilde{q}}$ | 10.4 TeV |
| $m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$ | 460 GeV | $m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$ | 549 GeV |
| $m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$ | 170 GeV | $m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$ | 178 GeV |
| $m_{\tilde{\tau}_1}$ | 97 GeV | $m_{\tilde{\tau}_1}$ | 113 GeV |
| $m_{\chi_1^0}$ | 277 GeV | $m_{\chi_1^0}$ | 292 GeV |
| $m_{\chi_1^\pm}$ | 730 GeV | $m_{\chi_1^\pm}$ | 857 GeV |
| δa_μ | 1.80×10^{-9} | δa_μ | 1.47×10^{-9} |

Table 1: *The mass spectrum and δa_μ for two different points. The bino mass, wino mass and higgsino mass parameters, defined at the scale, $m_{\tilde{t}}$, are also shown. As in Fig. 1, $\tan \beta = 10$.*

fitting formula presented in reference [21]. In both panels, we find a parameter region consistent with the experimental result of the muon $g - 2$ at 1.5σ level. Remarkably, the result can be explained almost 1σ level when the stop mass is about 8 TeV. It is worth noting that the constraint from the stability bound is severer for larger $\tan \beta$. No region consistent with the muon $g - 2$ result can be found for larger $\tan \beta$, such as $\tan \beta = 15$. In table 1, we show the part of the mass spectrum and δa_μ for two different points. Both left- and right-handed sleptons (smuons) as well as the bino are lighter than about 500 GeV, which are required to explain the muon $g - 2$, while the μ parameter is large as about 4 TeV. The colored SUSY particles are as heavy as 8 – 10 (10 – 12) TeV in the left (right) column. Notice that the right-handed sleptons are even lighter than 200 GeV in the region of the parameter space consistent with the muon $g - 2$ result within $1 - 1.5 \sigma$ level.

Due to the large μ -parameter and moderately large $\tan \beta$, the stau always tends to be very light in this scenario. In fact, in the region consistent with the experimental

result of the muon $g-2$, the stau is the next-to-lightest SUSY particle with its mass $m_{\tilde{\tau}} \lesssim 200$ GeV. When the R-parity is conserved, the stau is expected to decay into a gravitino by emitting a tau lepton with a long decay length (lifetime times the speed of light) and it can be regarded as a stable particle at collider experiments. Such a long-lived particle is, unfortunately, severely constrained to be $m_{\tilde{\tau}} > 270$ GeV [23]. We therefore need some mechanisms to make the stau decay promptly.

One of the simplest ways to have the prompt decay is use of the lepton number (R-parity) violating interactions, which are given by the superpotential,³

$$W_{L \neq 0} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k, \quad (11)$$

where we take the basis of superfields so that the bilinear term LH_u vanishes in the superpotential. The typical decay length of the stau is then estimated as

$$c\tau_{\tilde{\tau}} \sim \mathcal{O}(0.1 \text{ cm}) \left[\frac{(\lambda, \lambda')}{10^{-7}} \right]^{-2} \left(\frac{m_{\tilde{\tau}}}{100 \text{ GeV}} \right). \quad (12)$$

It is better to assume that the stau decays dominantly into a tau lepton and a neutrino, otherwise the stau mass tends to be constrained again by two jet resonance searches (through $L_i Q_j \bar{D}_k$ interactions) or searches using multi-lepton (electron/muon) channels at the LHC experiment. When the stau decays into a tau lepton and a neutrino, collider limits turn out to be very weak. Because all colored particles (gluino/squarks) are as heavy as $\mathcal{O}(10)$ TeV in this scenario, no limits on the stau mass has been obtained yet. Only the bound on the stau mass is from the LEP experiment, which gives the limit of $m_{\tilde{\tau}} > 95.9$ GeV [25].

The couplings λ and λ' which are much larger than $\mathcal{O}(10^{-7})$ are not favored, since otherwise the baryon asymmetry produced in the early epoch of the universe would be washed out [26]. The decay length of the stau therefore turns out definitely to be around $\mathcal{O}(mm)$, though it is hard to measure the corresponding impact parameter at the LHC experiment because of the small production cross section of the stau pair. Furthermore, if the lepton number is conserved in each flavor, one of λ_{ijk} (λ'_{ijk}) can be larger than $\mathcal{O}(10^{-7})$ without causing the washout of the baryon asymmetry [27], which leads to much shorter decay length of the stau than Eq.(12). In fact, lepton flavor violating terms do not arise in gauge mediation models, since the soft SUSY breaking masses of sleptons can be generated at a rather low-scale. It is also worth

³One might worry about the existence of baryon number interactions too, but it is known that there are models which does not have such interactions with being consistent with GUT [24].

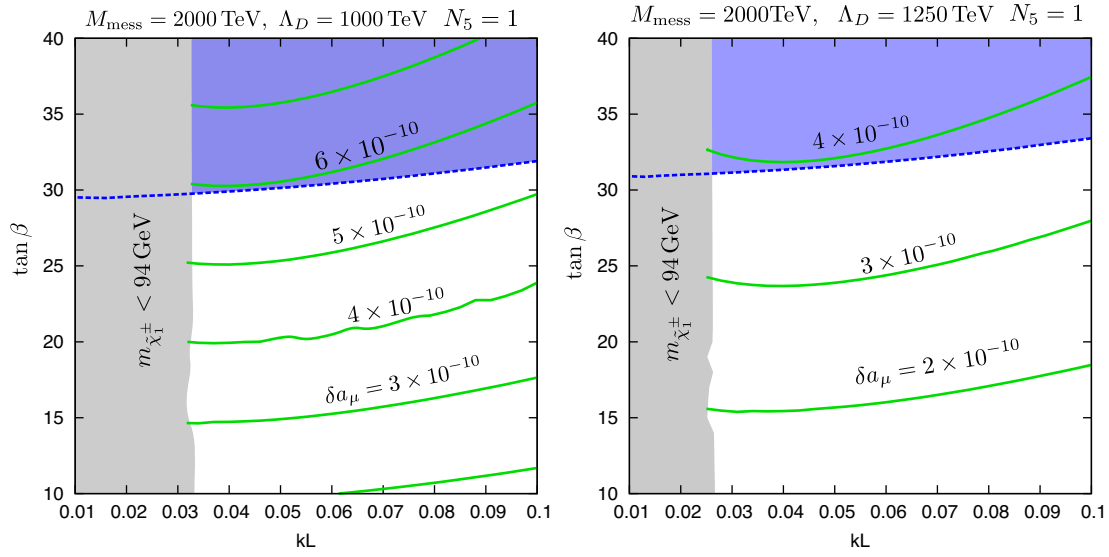


Figure 2: Contours of δa_μ on the k_L - $\tan \beta$ plane for $\Lambda_D = 1000$ (left) and 1250 TeV (right). The region above the dashed blue line is excluded because of the unstable electroweak symmetry minimum. The region limited by the chargino mass bound is also shown [22].

noting that, if the decay length is of the order of mm , the corresponding decay length can be observed at a future linear collider such as the ILC and CLIC [28].

Another interesting possibility to have the prompt decay of the stau is the introduction of other particles which can be decay products of the stau. For example, when the axino (supersymmetric partner of the axion) exists within appropriate mass range, the stau can decay into a tau lepton and the axino. Then, the decay length of the stau can be small enough if the PQ breaking scale is as low as $\sim 10^9$ GeV.

4 Additional Higgs soft squared masses

We next consider models with messengers in other than the adjoint representation. Before going to introduce the additional Higgs soft masses other than the gauge mediated SUSY breaking effects, let us first see how it is difficult to explain the 125 GeV Higgs mass and the deviation of the muon anomalous magnetic simultaneously in those representations. In figure 2, the parameter space of the model with messengers in fundamental representations is shown. Here, we parameterize the splitting of the F-term by k_L ,

$$W = (M_D + F\theta^2)\Psi_D\bar{\Psi}_D + (M_L + k_L F\theta^2)\Psi_L\bar{\Psi}_L, \quad (13)$$

where $\overline{\Psi}_D$ and Ψ_L are messenger multiplets which are transformed as $(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$ and $(\mathbf{1}, \mathbf{2}, -1/2)$ under the SM gauge groups, respectively. As in the case of the adjoint messenger, we take a common SUSY mass, i.e., $M_L = M_D = M_{\text{mess}} = 2 \times 10^6$ GeV. In the left (right) panel of the figure, $\Lambda_D \equiv F/M_D$ is taken to be $\Lambda_D = 1000$ (1250) TeV, which corresponds to the stop mass of $m_{\tilde{t}} \simeq 8$ (10) TeV. The bino and higgsino masses are turns out to be $M_1 \simeq 600$ (800) GeV and $\mu \simeq 4000$ (4900) GeV, respectively, in the left (right) panel. Since neither bino nor higgsino are light, δa_μ cannot reach to the value of $\sim 10^{-9}$; the observed value of the muon $g - 2$ can not be explained even with the splitting F-terms.

In the case of messengers in anti-symmetric representations of $SU(5)$, i.e., $\mathbf{10} + \overline{\mathbf{10}}$, the messenger multiplets Ψ_Q ($SU(2)_L$ doublet) and Ψ_U ($SU(2)_L$ singlet) have color charges. When the squark masses are generated dominantly from Ψ_U , the bino and slepton masses are heavier than those of the fundamental messenger case due to the larger hyper-charge of Ψ_U . When the squark masses are dominantly generated by Ψ_Q , the left-handed sleptons and wino cannot be light, because Ψ_Q has a $SU(2)_L$ charge. As a result, it is more difficult to enhance δa_μ in the $\mathbf{10} + \overline{\mathbf{10}}$ case.

Now, let us introduce additional soft squared masses to the Higgs doublets in the model with the messengers in the fundamental representation. As we have mentioned in Introduction, the additional Higgs soft masses allows the small μ -term, which enhances the wino-higgsino contributions to the $g - 2$. Such additional contributions can be generated if the Higgs doublets couple to the SUSY breaking sector. For example, let us take a SUSY breaking O’Reifeartaigh model coupling to the Higgs doublets via,

$$W = m^2 Z + \frac{\kappa}{2} Z X^2 + M_{XY} XY + \lambda X H_u H_d . \quad (14)$$

Here, Z is a SUSY breaking field with a non-vanishing F -term, i.e. $\langle F_Z \rangle = m^2$, and X, Y are the singlet fields. With the above interactions, the Higgs doublets receive non-vanishing and positive soft squared masses at the one-loop level,

$$\delta m_{H_{u,d}}^2 = \frac{\lambda^2}{32\pi^2} \frac{\tilde{F}^2}{M_{XY}^2} \left(1 + \mathcal{O}(\tilde{F}^2/M_{XY}^4) \right) , \quad (15)$$

where $\tilde{F} = \kappa m^2$. In this way, we obtain desired additional soft squared Higgs masses by arranging parameters appropriately.⁴

⁴In this model, the μ -term nor B -term are not generated through the above interactions, which are forbidden by a Z_4 symmetry under which X and Y change signs. It is also possible to consider

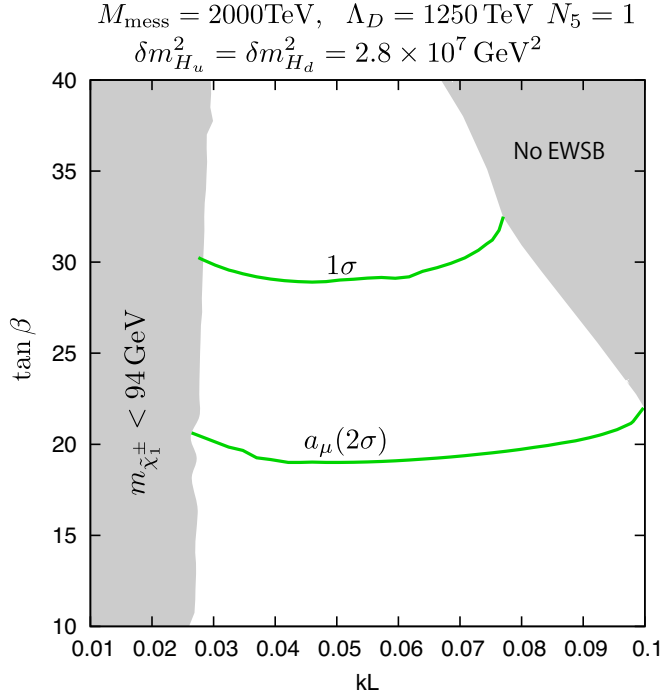


Figure 3: Contours of a_μ consistent with the experimental result at 1 and 2σ C.L. on the k_L - $\tan\beta$ plane for $\Lambda_D = 1250$ TeV. Additional contributions to $m_{H_u}^2$ and $m_{H_d}^2$ are taken to be $\delta m_{H_u}^2 = \delta m_{H_d}^2 = 2.8 \times 10^7$ GeV², respectively. The gray regions are excluded by chargino searches at the LEP experiment, or unsuccessful electroweak symmetry breaking.

In the followings, we take the additional soft terms as free parameters and assume that they are generated at around the messenger scale. With the additional contributions to the Higgs soft square masses, $\delta m_{H_u}^2$ and $\delta m_{H_d}^2$, the μ -parameter can be small (see Eq.(8)). Thus, in this case, the higgsinos can be light as $\mathcal{O}(100)$ GeV, and hence, δa_μ can be large enough. In figure 3, contours of a_μ consistent with the experimental result at 1 and 2σ C.L. are shown. The figure shows that the observed value of the anomalous magnetic moment can be explained within 1σ level. The typical value of the μ -parameter is less than about 300 GeV in the region consistent with the observed value within 2σ level. In table 2, we show a mass spectrum and δa_μ as a reference. The bino and sleptons are heavier than 700 GeV. On the other hand, the higgsino and wino are as light as 200 GeV and 160 GeV, respectively; δa_μ is enhanced with the help of the light higgsino and wino. The colored SUSY particles

models where the μ -term is also generated while keeping the B -term suppressed via the couplings between the Higgs doublets and O’Raifeartaigh model [29]. In such models with μ -term generation, it is predicted that μ -term is rather suppressed than $\delta m_{H_{u,d}}$.

are as heavy as $8.6 - 11$ TeV, which are required to explain the Higgs boson mass of around 125 GeV.

In this model, the wino-like neutralino is the next-to-lightest SUSY particle. Since the gluino and squarks are as heavy as $\mathcal{O}(10)$ TeV, collider limits are much weaker than those of conventional SUSY models. At present, the most sensitive mode related to the wino search at the LHC experiment comes from the direct wino pair production associated with a jet [30]. In this analysis, the disappearing charged track at inner detectors caused by the long-life of the charged wino (corresponding to the decay length of about 5 cm when the wino-higgsino mixing is negligible) is utilized to reduce SM backgrounds. The transition radiation tracker (TRT) is currently used to find the track. Since the TRT is located about 1 m away from the beam pipe, the limit on the wino mass is rather weak, i.e., the limit is $m_{\text{wino}} > 100$ GeV [31]. The most inner detectors such as pixel and SCT detectors are planned to be used in near future, and then the wino mass up to about 500 GeV will be covered.

5 Summary

In this paper, we have discussed whether or not the 125 GeV Higgs boson mass and the discrepancy of the magnetic moment a_μ can be simultaneously explained in models with heavy squarks and light sleptons. Such a simple possibility turns out to be highly constrained and we found that models with adjoint **24** messengers are the unique possibility. In these models, the discrepancy of a_μ between theoretical prediction and experimental result can be reduced to about 1.5σ (1σ) C.L. for the stop mass of about 10 TeV (8 TeV). In such a region consistent with the experimental result of the muon $g - 2$, the stau is the next to the lightest SUSY particle with the mass of less than about 200 GeV. In the light of the constraint from the LHC experiments, such a light stau should decay promptly via a R-parity violating operator (lepton number violating operator). It should be emphasized that the gravitino is still a viable candidate for dark matter because the violation of the R-parity is small.

On the other hand, once we admit additional contributions to Higgs soft masses, we found that models with the messengers in the fundamental $\mathbf{5} + \bar{\mathbf{5}}$ representations can also explain the 125 GeV Higgs boson mass and the experimental result of the anomalous magnetic moment simultaneously. In these models, the predicted a_μ can be consistent with its experimental result within 1σ C.L. even for the stop mass of

| | |
|--------------------------------------|---------------------------------|
| M_{mess} | 2000 TeV |
| Λ_D | 1250 TeV |
| N_5 | 1 |
| $\tan \beta$ | 32 |
| k_L | 0.05 |
| $\delta m_{H_{u,d}}^2$ | $2.8 \times 10^7 \text{ GeV}^2$ |
| M_{bino} | 827 GeV |
| M_{wino} | 163 GeV |
| μ | 211 GeV |
| m_{gluino} | 8.6 TeV |
| $m_{\tilde{t}}$ | 10.1 TeV |
| $m_{\tilde{q}}$ | 11.0 TeV |
| $m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$ | 731 GeV |
| $m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$ | 1398 GeV |
| $m_{\tilde{\tau}_1}$ | 592 GeV |
| $m_{\chi_1^0}$ | 143 GeV |
| $m_{\chi_1^\pm}$ | 145 GeV |
| δa_μ | 2.11×10^{-9} |

Table 2: The mass spectrum and δa_μ . The bino mass, wino mass and higgsino mass parameters are also shown.

about 10 TeV. Although the additional Higgs soft masses are required, these masses may be related to the origin of $\mu/B\mu$ term, that is, the solution for the $\mu/B\mu$ problem in gauge mediation models.

Acknowledgements

This work is supported by the Grant-in-Aid for Scientific research from the Ministry of Education, Science, Sports, and Culture (MEXT), Japan, No. 24740151 (M.I.), No. 22244021 (S.M. and T.T.Y.), No. 23740169 (S.M.), and also by the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan. The work of N.Y. is supported in part by JSPS Research Fellowships for Young Scientists.

A Gaugino and scalar masses

Here, we summarize gaugino and scalar masses predicted by gauge mediation models with messenger multiplets in various representations. Note that g_1 is the coupling constant of $U(1)_Y$ gauge interaction with the GUT normalization

A.1 $5+\bar{5}$ messenger

Gaugino masses are given by

$$M_1 \simeq \frac{g_1^2}{16\pi^2} N_5 \left(\frac{2}{5} \Lambda_D + \frac{3}{5} \Lambda_L \right), \quad M_2 \simeq \frac{g_2^2}{16\pi^2} N_5(\Lambda_L), \quad M_3 \simeq \frac{g_3^2}{16\pi^2} N_5(\Lambda_D), \quad (16)$$

where $\Lambda_D = F_D/M_D$ and $\Lambda_L = F_L/M_L$. Here, sub-leading contributions are neglected. Scalar masses are, on the other hand, given by

$$\begin{aligned} m_{\tilde{Q}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{4} g_2^4 \Lambda_L^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5} \Lambda_D^2 + \frac{3}{5} \Lambda_L^2 \right) \frac{1}{6^2} \right], \\ m_{\tilde{U}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5} \Lambda_D^2 + \frac{3}{5} \Lambda_L^2 \right) \left(\frac{2}{3} \right)^2 \right], \\ m_{\tilde{D}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5} \Lambda_D^2 + \frac{3}{5} \Lambda_L^2 \right) \frac{1}{3^2} \right], \\ m_{\tilde{L}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{3}{4} g_2^4 \Lambda_L^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5} \Lambda_D^2 + \frac{3}{5} \Lambda_L^2 \right) \frac{1}{2^2} \right], \\ m_{\tilde{E}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{3}{5} g_1^4 \left(\frac{2}{5} \Lambda_D^2 + \frac{3}{5} \Lambda_L^2 \right) \right], \\ m_{H_u}^2 &= m_{H_d}^2 = m_{\tilde{L}}^2. \end{aligned} \quad (17)$$

A.2 $10 + \bar{10}$ messenger

Gaugino masses are given by

$$\begin{aligned} M_1 &\simeq \frac{g_1^2}{16\pi^2} \left(\frac{1}{5} \Lambda_Q + \frac{8}{5} \Lambda_U + \frac{6}{5} \Lambda_E \right), \quad M_2 \simeq \frac{g_2^2}{16\pi^2} (3\Lambda_Q), \\ M_3 &\simeq \frac{g_3^2}{16\pi^2} (2\Lambda_Q + \Lambda_U), \end{aligned} \quad (18)$$

where $\Lambda_Q = F_Q/M_Q$, $\Lambda_U = F_U/M_U$ and $\Lambda_E = F_E/M_E$. Scalar masses are given by

$$\begin{aligned}
m_{\tilde{Q}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3}g_3^4\tilde{\Lambda}_3^2 + \frac{3}{4}g_2^4(3\Lambda_Q^2) + \frac{3}{5}g_1^4(\tilde{\Lambda}_1^2)\frac{1}{6^2} \right], \\
m_{\tilde{U}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3}g_3^4\tilde{\Lambda}_3^2 + \frac{3}{5}g_1^4\tilde{\Lambda}_1^2 \left(\frac{2}{3}\right)^2 \right], \\
m_{\tilde{D}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3}g_3^4\tilde{\Lambda}_3^2 + \frac{3}{5}g_1^4\tilde{\Lambda}_1^2\frac{1}{3^2} \right], \\
m_{\tilde{L}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{3}{4}g_2^4(3\Lambda_Q^2) + \frac{3}{5}g_1^4\tilde{\Lambda}_1^2\frac{1}{2^2} \right], \\
m_{\tilde{E}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{3}{5}g_1^4\tilde{\Lambda}_1^2 \right], \\
m_{H_u}^2 &= m_{H_d}^2 = m_{\tilde{L}}^2,
\end{aligned} \tag{19}$$

where $\tilde{\Lambda}_1^2 = (\Lambda_Q^2 + 8\Lambda_U^2 + 6\Lambda_E^2)/5$ and $\tilde{\Lambda}_3^2 = 2\Lambda_Q^2 + \Lambda_U^2$, respectively.

A.3 Adjoint messenger

Gaugino masses are given by

$$M_1 \simeq \frac{g_1^2}{16\pi^2}(5\Lambda_X), \quad M_2 \simeq \frac{g_2^2}{16\pi^2}(2\Lambda_3 + 3\Lambda_X), \quad M_3 \simeq \frac{g_3^2}{16\pi^2}(3\Lambda_8 + 2\Lambda_X), \tag{20}$$

where $\Lambda_8 = F_8/M_8$, $\Lambda_3 = F_3/M_3$ and $\Lambda_X = F_X/M_X$. Scalar masses are given by

$$\begin{aligned}
m_{\tilde{Q}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3}g_3^4(3\Lambda_8^2 + 2\Lambda_X^2) + \frac{3}{4}g_2^4(2\Lambda_3^2 + 3\Lambda_X^2) + \frac{3}{5}g_1^4(5\Lambda_X^2)\frac{1}{6^2} \right], \\
m_{\tilde{U}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3}g_3^4(3\Lambda_8^2 + 2\Lambda_X^2) + \frac{3}{5}g_1^4(5\Lambda_X^2) \left(\frac{2}{3}\right)^2 \right], \\
m_{\tilde{D}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{4}{3}g_3^4(3\Lambda_8^2 + 2\Lambda_X^2) + \frac{3}{5}g_1^4(5\Lambda_X^2)\frac{1}{3^2} \right], \\
m_{\tilde{L}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{3}{4}g_2^4(2\Lambda_3^2 + 3\Lambda_X^2) + \frac{3}{5}g_1^4(5\Lambda_X^2)\frac{1}{2^2} \right], \\
m_{\tilde{E}}^2 &\simeq \frac{2}{(16\pi^2)^2} \left[\frac{3}{5}g_1^4(5\Lambda_X^2) \right], \\
m_{H_u}^2 &= m_{H_d}^2 = m_{\tilde{L}}^2.
\end{aligned} \tag{21}$$

References

- [1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012).
- [2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012).

- [3] Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. **85**, 1 (1991); J. R. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B **257**, 83 (1991); H. E. Haber and R. Hempfling, Phys. Rev. Lett. **66**, 1815 (1991).
- [4] Y. Okada, M. Yamaguchi and T. Yanagida, Phys. Lett. B **262**, 54 (1991).
- [5] M. Ibe and T. T. Yanagida, Phys. Lett. B **709**, 374 (2012) [arXiv:1112.2462 [hep-ph]]; M. Ibe, S. Matsumoto and T. T. Yanagida, Phys. Rev. D **85**, 095011 (2012) [arXiv:1202.2253 [hep-ph]]; B. Bhattacharjee, B. Feldstein, M. Ibe, S. Matsumoto and T. T. Yanagida, arXiv:1207.5453 [hep-ph].
- [6] T. Moroi and Y. Okada, Mod. Phys. Lett. A **7**, 187 (1992); T. Moroi and Y. Okada, Phys. Lett. B **295**, 73 (1992); K. S. Babu, I. Gogoladze, M. U. Rehman and Q. Shafi, Phys. Rev. D **78**, 055017 (2008) [arXiv:0807.3055 [hep-ph]]; S. P. Martin, Phys. Rev. D **81**, 035004 (2010) [arXiv:0910.2732 [hep-ph]].
- [7] P. Batra, A. Delgado, D. E. Kaplan and T. M. P. Tait, JHEP **0402**, 043 (2004) [hep-ph/0309149]; A. Maloney, A. Pierce and J. G. Wacker, JHEP **0606**, 034 (2006) [hep-ph/0409127].
- [8] M. Maniatis, Int. J. Mod. Phys. A **25**, 3505 (2010) [arXiv:0906.0777 [hep-ph]].
- [9] U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. **496**, 1 (2010) [arXiv:0910.1785 [hep-ph]].
- [10] J. L. Evans, M. Ibe, S. Shirai and T. T. Yanagida, Phys. Rev. D **85**, 095004 (2012).
- [11] M. Endo, K. Hamaguchi, S. Iwamoto and N. Yokozaki, Phys. Rev. D **84**, 075017 (2011); M. Endo, K. Hamaguchi, S. Iwamoto and N. Yokozaki, Phys. Rev. D **85**, 095012 (2012).
- [12] K. Nakayama, N. Yokozaki and N. Yokozaki, arXiv:1204.5420 [hep-ph].
- [13] M. Endo, K. Hamaguchi, S. Iwamoto, K. Nakayama and N. Yokozaki, Phys. Rev. D **85**, 095006 (2012) [arXiv:1112.6412 [hep-ph]].
- [14] G. W. Bennett *et al.* [Muon G-2 Collaboration], Phys. Rev. D **73**, 072003 (2006).
- [15] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, J. Phys. G **38**, 085003 (2011).
- [16] J. L. Evans, M. Ibe and T. T. Yanagida, Phys. Lett. B **705**, 342 (2011).

- [17] G. -C. Cho, K. Hagiwara, Y. Matsumoto and D. Nomura, JHEP **1111**, 068 (2011).
- [18] A. Djouadi, J. -L. Kneur and G. Moultaka, Comput. Phys. Commun. **176**, 426 (2007).
- [19] S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. **124**, 76 (2000); S. Heinemeyer, W. Hollik and G. Weiglein, Eur. Phys. J. C **9**, 343 (1999); G. Degrandi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, Eur. Phys. J. C **28**, 133 (2003); JHEP **0702**, 047 (2007).
- [20] R. Rattazzi and U. Sarid, Nucl. Phys. B **501**, 297 (1997).
- [21] J. Hisano and S. Sugiyama, Phys. Lett. B **696**, 92 (2011).
- [22] J. Beringer et al. (Particle Data Group), Phys. Rev. D **86**, 010001 (2012)
- [23] The ATLAS Collaboration, ATLAS-CONF-2012-075.
- [24] L. J. Hall and M. Suzuki, Nucl. Phys. B **231**, 419 (1984); D. E. Brahm and L. J. Hall, Phys. Rev. D **40**, 2449 (1989); W. Buchmuller, L. Covi, K. Hamaguchi, A. Ibarra and T. Yanagida, JHEP **0703**, 037 (2007).
- [25] A. Heister *et al.* [ALEPH Collaboration], Eur. Phys. J. C **31**, 1 (2003); S. Braibant, hep-ex/0305058.
- [26] B. A. Campbell, S. Davidson, J. R. Ellis and K. A. Olive, Phys. Lett. B **256** (1991) 457; W. Fischler, G. F. Giudice, R. G. Leigh and S. Paban, Phys. Lett. B **258** (1991) 45; H. K. Dreiner and G. G. Ross, Nucl. Phys. B **410** (1993) 188 [arXiv:hep-ph/9207221].
- [27] M. Endo, K. Hamaguchi and S. Iwamoto, JCAP **1002**, 032 (2010).
- [28] S. Matsumoto and T. Moroi, Phys. Lett. B **701**, 422 (2011).
- [29] M. Ibe and R. Kitano, JHEP **0708**, 016 (2007) [arXiv:0705.3686 [hep-ph]].
- [30] J. L. Feng, T. Moroi, L. Randall, M. Strassler and S. -f. Su, Phys. Rev. Lett. **83**, 1731 (1999); M. Ibe, T. Moroi and T. T. Yanagida, Phys. Lett. B **644**, 355 (2007); T. Moroi and K. Nakayama, Phys. Lett. B **710**, 159 (2012); B. Bhattacharjee, B. Feldstein, M. Ibe, S. Matsumoto and T. T. Yanagida, arXiv:1207.5453 [hep-ph].
- [31] The ATLAS Collaboration, ATLAS-CONF-2012-111.